

# The ultra luminous X-ray source NuSTAR J095551+6940.8: A magnetar in a high mass X-ray binary

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## ABSTRACT

The recent detection of pulsations from the ultra luminous X-ray source (ULX) NuSTAR J095551+6940.8 in M82 by Bachetti et al. indicates that the object is an accreting neutron star in a high mass X-ray binary (HMXB) system. The super-Eddington luminosity of the object implies that the magnetic field is sufficiently strong to suppress the scattering cross-section unless its beam is viewed at a favourable angle. We show that the torque equilibrium condition for the pulsar indicates the dipole magnetic field of the neutron star is  $6.7 \times 10^{13}$  G, two orders of magnitude higher than that estimated by Bachetti et al., and further point to the possibility that even stronger magnetic fields could well be in the higher multipoles. This supports the recent view that magnetars descend from HMXBs if the magnetic field decays an order of magnitude during the process of transition.

**Key words:** X-rays: binaries, X-rays: ULXs, X-rays: individual NuSTAR J095551+6940.8

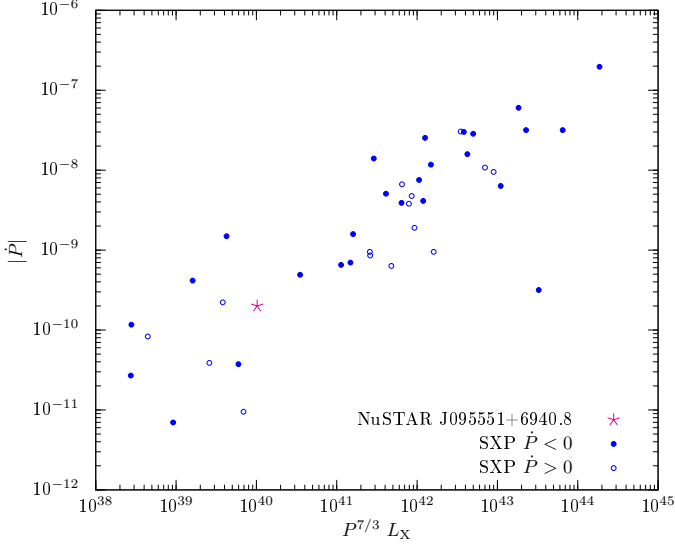
## 1 INTRODUCTION

Ultra-luminous X-ray sources (ULXs) are accreting compact objects with luminosities exceeding the Eddington limit  $L_E = 4\pi G M m_p c / \sigma_T = 1.3 \times 10^{38} (M/M_\odot) \text{ erg s}^{-1}$  ( $M$  is the mass of the accreting object,  $m_p$  is the mass of the proton,  $c$  is the speed of light,  $G$  is the gravitational constant and  $\sigma_T$  is the Thomson cross-section for scattering of photons from electrons) for a  $\sim 10 M_\odot$  object (see Roberts 2007, for a review). They possibly form a heterogeneous family with sub-classes (Gladstone 2013). Some of these objects reach luminosities  $10^{41} \text{ erg s}^{-1}$  appropriate for  $M \sim 10^3 M_\odot$  under the assumption of accretion at the Eddington limit. Such objects are puzzling as they can not form by stellar evolution and are dubbed intermediate mass black holes (Kong et al. 2004; Miller et al. 2004; Liu & Di Stefano 2008). Alternatively, they are proposed to be stellar mass black holes accreting at rates slightly exceeding the Eddington limit (Gladstone et al. 2009) and appear to be super-Eddington due to anisotropic emission.

The recent identification (Bachetti et al. 2014) of NuSTAR J09551+6940.8 in the nearby galaxy M82 with a neutron star accreting in a high mass X-ray binary (HMXB) challenged the view that all ULX harbour black holes. The luminosity of the object is  $4 \times 10^{39} \text{ erg s}^{-1}$  during pulsations and reaches  $3.7 \times 10^{40} \text{ erg s}^{-1}$  at the peak flux under the assumption of isotropic emission. As a neutron star can not have a mass exceeding  $\sim 3.5 M_\odot$  (Rhoades & Ruffini 1974)

this super-Eddington luminosity is attributed by Bachetti et al. (2014) to fan beam geometry (Gnedin & Sunyaev 1973) viewed at a favourable angle. An alternative explanation obviating the assumption of favourable viewing angle though not necessarily rejecting that the emission is anisotropic, is that the magnetic field is so strong that the scattering cross-section reduces (Canuto et al. 1971) as is the case for magnetars (Duncan & Thompson 1992; Thompson & Duncan 1996; Paczynski 1992). This explanation is not preferred by (Bachetti et al. 2014) as they infer the magnetic dipole field of the neutron star to be  $B \sim 10^{12}$  G from the observed spin-up rate assuming accretion at the Eddington rate. This value for the magnetic field inferred by (Bachetti et al. 2014) is not consistent with the assumption of the system being near torque equilibrium because the torque for a system near equilibrium is vanishingly small and leads to an underestimate of the magnetic field if its full value is employed. A magnetic field as low as  $B \sim 10^{12}$  G is also not consistent with the presence of fan beam geometry. An increase in the critical luminosity by beaming is easier to achieve with a field of the order of  $10^{13}$  G (Basko & Sunyaev 1975).

In this *letter* we show that the pulsar in NuSTAR J09551+6940.8 has a dipole magnetic field of at least  $B \sim 10^{13}$  G—in the range of low-magnetic field magnetars (Rea et al. 2010)—and possibly of  $B \sim 10^{14}$  G in excess of the quantum critical limit,  $B_c \equiv m_e^2 c^3 / \hbar e = 4.4 \times 10^{13}$  G, and argue that it could have even stronger magnetic fields in the higher multipoles (Ekşi & Alpar 2003). Such strong



**Figure 1.** Period derivative  $|\dot{P}|$  versus  $L_X P^{7/3}$  diagram [Ghosh & Lamb \(1979b\)](#) for X-ray pulsars in Be/HMXBs of Small Magellanic Clouds ([Klus et al. 2014](#)) (SXPs) together with NuSTAR J09551+6940.8 where we used  $P = 1.37$ ,  $\dot{P} = 2 \times 10^{-10} \text{ s s}^{-1}$  and  $L_X = 4.9 \times 10^{39} \text{ erg s}^{-1}$  ([Bachetti et al. 2014](#)).

fields increase the critical luminosity either by releasing the energy via magnetohydrodynamic waves ([Katz 1996](#)) or by the reduction of the scattering cross section ([Canuto et al. 1971](#)). This relates at least some of the ULXs with isolated magnetars and supports the recent view that magnetars descend from HMXBs ([Bisnovatyi-Kogan & Ikhshanov 2014](#)). In the following section we estimate the magnetic field of the accreting neutron star in NuSTAR J09551+6940.8 and in §3 we discuss its astrophysical implications.

## 2 THE MAGNETIC FIELD OF NuSTAR J09551+6940.8 AND ITS CRITICAL LUMINOSITY

The X-ray luminosity due to accretion of matter onto a compact object is

$$L_X = \frac{GMM}{R} \quad (1)$$

where  $R$  is the radius of the neutron star. This implies  $\dot{M} = 0.535 \times 10^{20} \text{ g s}^{-1} L_{40} R_6 m^{-1}$  where  $L_{40} = L/10^{40} \text{ erg s}^{-1}$ ,  $R_6 = R/10^6 \text{ cm}$  and  $m = M/1.4M_\odot$ . Normally, this much luminosity would not be able to accrete onto the star because of the radiation pressure. Yet, we assume the critical luminosity is increased beyond the Eddington limit by the suppressed scattering cross-section of the electrons in strong magnetic field ([Canuto et al. 1971](#); [Herold 1979](#); [Paczynski 1992](#)) or by the transportation of energy via magnetohydrodynamic waves ([Katz 1996](#)).

The torque on the neutron star is  $N = I\dot{\Omega} = 6 \times 10^{35} I_{45} \text{ g cm}^2 \text{ s}^{-2}$  where  $I_{45}$  is the moment of inertia in units of  $10^{45} \text{ g cm}^2$  as inferred from the observed spin-up rate of  $\dot{P} \sim -2 \times 10^{-10} \text{ s s}^{-1}$  ([Bachetti et al. 2014](#)). As  $P/\dot{P} \sim 300$  years the system should be near torque equilibrium so that the inner radius of the disc is close to the corotation radius  $R_c = (GMP^2/4\pi^2)^{1/3}$ . More specifically

it will be  $R_{\text{in}} = \omega_c^{2/3} R_c$  where  $\omega_c$  is the critical fastness parameter at which torque vanishes and is of order unity. The fastness parameter is defined as  $\omega_* = (R_{\text{in}}/R_c)^{3/2}$  ([Elsner & Lamb 1977](#)). The measured period of the neutron star,  $P = 1.37 \text{ s}$ , implies that the co-rotation radius is at  $R_c = 2.1 \times 10^8 m^{3/2} \text{ cm}$ . The inner radius of the disc is thus at

$$R_{\text{in}} = 2.1 \times 10^8 m^{3/2} \omega_c^{2/3} \text{ cm}. \quad (2)$$

The inner radius of the disc is determined by the balance of magnetic and material stresses ([Ghosh & Lamb 1979a,b](#)) and scales with the Alfvén radius ([Davidson & Ostriker 1973](#))

$$R_{\text{in}} = \xi \left( \frac{\mu^2}{\sqrt{2GM\dot{M}}} \right)^{2/7} \quad (3)$$

where  $\xi$  is a dimensionless number of order unity. Equating the last two equations we find the magnetic dipole moment of the neutron star as  $\mu = 1.17 \times 10^{31} \omega_c^{7/6} \xi^{-7/4} m^{1/3} L_{40}^{1/2} R_6^{1/2}$  which, by  $\mu = \frac{1}{2} BR^3$ , implies

$$B = 2 \times 10^{13} \omega_c^{7/6} \xi^{-7/4} m^{1/3} L_{40}^{1/2} R_6^{-5/2} \text{ G}. \quad (4)$$

This value is an order of magnitude larger than that found by [Bachetti et al. \(2014\)](#) who use the measured torque to estimate the magnetic field. For  $\xi = 0.5$ , favoured by [Ghosh & Lamb \(1979a\)](#), the field is found to be even larger,  $B = 6.7 \times 10^{13} \text{ G}$ , in excess of the quantum critical limit  $B_c$ . The torque, however, is smaller than its nominal value  $N_0 = \sqrt{GMR_{\text{in}}\dot{M}}$  ([Pringle & Rees 1972](#)) as the system is near torque equilibrium. The nominal value should not be used for estimating the magnetic moment in this case as it would give a lowest estimate for the magnetic field. The torque acted by the disc, in general, is given as

$$N = n(\omega_*) N_0 \quad (5)$$

where  $n(\omega_*)$  is the dimensionless torque ([Ghosh & Lamb 1979a,b](#)). Any torque model near torque equilibrium would be of the form  $n = 1 - \omega_*/\omega_c$ . This then would lead to the equation

$$-I\dot{P}/P^2 = \left(1 - \frac{\omega_*}{\omega_c}\right) \omega_*^{1/3} \sqrt{GMR_c} \dot{M} \quad (6)$$

where we used  $N = -I\dot{P}/P^2$ . We solve this equation which is of the form  $(1-x)x^{1/3} = \text{constant}$  where  $x = \omega_*/\omega_c$  numerically for the fastness parameter of the system and find  $\omega_* \simeq 0.9$  for  $\omega_c = 1$ ,  $P = 1.37$ ,  $\dot{P} = 2 \times 10^{-10} \text{ s s}^{-1}$  and  $L_X = 4.9 \times 10^{39} \text{ erg s}^{-1}$  ([Bachetti et al. 2014](#)). This indeed shows that the system is near torque equilibrium, but leads to a magnetic field  $0.9^{7/6} \simeq 0.88$  times smaller than that inferred in [Equation 4](#). The above relations lead to

$$|\dot{P}| \propto (L_X P^{7/3})^{6/7} \quad (7)$$

([Ghosh & Lamb 1979b](#)) for  $\omega_* \ll \omega_c$  and this relation may be used as a diagnostic for understanding the accretion stage of NuSTAR J09551+6940.8. Accordingly, [Figure 1](#) shows NuSTAR J09551+6940.8 among X-ray pulsars in Be/HMXBs of the Small Magellanic Clouds (SXPs) ([Klus et al. 2014](#)) in a  $|\dot{P}|$  versus  $L_X P^{7/3}$  digram. The SXPs in the data set of [Klus et al. \(2014\)](#) are the ones accreting from a disc rather than a wind. The ordinary position of NuSTAR J09551+6940.8 in the diagram also suggests that the object is indeed near

torque equilibrium just like most of the SXP's though NuSTAR J09551+6940.8 is likely to accrete via Roche-lobe overflow while SXP would be accreting from Be discs.

### 3 DISCUSSION AND CONCLUSION

We have found that the dipole magnetic field of the pulsar NuSTAR J09551+6940.8 is at least  $2 \times 10^{13}$  G, an order of magnitude larger than that inferred by (Bachetti et al. 2014) and possibly even stronger,  $6.7 \times 10^{13}$  G, in excess of the quantum critical magnetic field  $B_c$ , if the inner radius of the disc is half of the Alfvén radius. Such a super-strong field is sufficient to lead to a reduction of the scattering cross-section and increase the critical luminosity (Paczynski 1992). It is possible that the object has even stronger magnetic fields in the higher multipoles leading to even more effective increase of the critical luminosity enabling luminosities as large as  $10^3 L_E$ .

Such strong fields are reminiscent of the magnetars (Duncan & Thompson 1992) in our own galaxy which are envisaged as isolated objects (Thompson & Duncan 1996). Recently, Bisnovaty-Kogan & Ikhsanov (2014) suggested a scenario in which magnetars descend from HMXBs. The magnetic fields suggested for magnetars by these authors, however, is an order of magnitude lower than that estimated for NuSTAR J09551+6940.8 in the present paper. This implies that, if the scenario is correct, the magnetic field of NuSTAR J09551+6940.8 should decay during the process of transition to the isolated magnetar stage. The decay of the magnetic field of a neutron star by accretion is a process also invoked in the context of millisecond pulsars descending from low mass X-ray binaries (Bisnovaty-Kogan & Komberg 1976; Alpar et al. 1982; Radhakrishnan & Srinivasan 1982).

There had been claims for the presence of accreting neutron stars with such strong magnetic fields in other HMXBs (Reig et al. 2012; Bozzo et al. 2008; Popov & Turolla 2012; Finger et al. 2010; Ikhsanov & Beskrovnaya 2010; Klus et al. 2013; Fu & Li 2012, see e.g.) though none had been caught in such a ultra-luminous state as NuSTAR J09551+6940.8. Also the neutron stars in these systems are accreting from the wind of the companion and have very long spin periods,  $P \sim 10^3$  s. More interestingly, magnetar-like behaviour from the peculiar binary LS I +61°303 is reported (Torres et al. 2012). The presence of such strong magnetic fields in some of these systems, however, has recently been questioned by (Postnov et al. 2014) who employed the quasi-spherical accretion model of Shakura et al. (2012). NuSTAR J09551+6940.8, however, is very different from these systems with its much shorter period and much higher luminosity.

For such strong magnetic fields the electron-cyclotron line would be beyond 500 keV which is undetectable by X-ray detectors. The proton-cyclotron lines have energies  $E \sim 0.5(B/10^{14} \text{ G}) = 0.5 \text{ keV}$  and could be detected by *XMM-Newton*. We would, however, like to note that no significant proton-cyclotron line had been detected in the persistent X-ray emission of isolated magnetars. Hence the null result of such a search would not immediately rule out that the magnetic field of this object is of magnetar strength.

The question naturally arises whether most if not all ULXs could be super-strongly magnetized accreting neu-

tron stars. Soon after this paper was submitted Doroshenko et al. (2014) presented the null result of their search of pulsations through available archival *XMM-Newton* observations of several ULX. At highest accretion rates the pulsar could be enshrouded and the pulsations could be smeared out by the optically thick surrounding medium. This may address the elusiveness of pulsations from other ULXs and may indicate to a larger population of neutron stars among ULXs. Accordingly, ULXs at their lowest luminosity stage are better targets for detecting pulsations.

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